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Investigations of Mode Control in Proton-Implanted and Oxide-Confined VCSELs Using PBGs: Modelling and Experiment

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ABSTRACT
We have investigated theoretically the influence of a two-dimensional photonic crystal (PC) defect waveguide embedded into vertical-cavity surface-emitting lasers on transverse optical modes. In gain-guided structures, where the index profile is weak, the effect of the PC is efficient. In the oxide-confined structures, where the index guidance provided by the oxide is larger, this is not the case, but the efficiency of the PC can be increased by oxide in node position. It was shown, that the thermal lensing effect leads to increased sensitivity of the single-mode conditions on the current injection change.

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) are key components of optical sources in low-cost short-distance optical links because of their characteristics such as a low threshold current, single longitudinal mode operation, circular shape of the output beam, wafer-scale integration and high-speed data transmission. Further increase of the transmission distance in such optical links can by satisfied by increasing the optical power, which assumes an increase of the transverse current confinement size. It is possible to introduce optical and electrical confinement through proton or oxide implant [1]. These result in an optical confinement due to gain- and index waveguiding mechanisms. An increase of the oxide or the proton confinement size leads to an increase of transverse mode number in the VCSEL cavity and results in degrading the modulation [2] and noise performance [3] and dispersion properties of optical links.

In recent years, the two-dimensional photonic crystal (PC) as a periodic modulation of the refractive index in a plane have been applied in order to improve the transverse optical confinement in VCSELs [4-7]. It has been demonstrated that the two-dimensional PC created by air-holes and positioned in VCSEL cavities establishes the single-mode at relatively large laser beam aperture in comparison with conventional VCSELs [5]. The group of theoretical methods for investigation of single-mode conditions in VCSELs with incorporated two-dimensional PC have recently been proposed [5,6,8]. However, the active conditions taking place in realistic VCSELs and the resulting local refractive index change in such PC waveguides were not considered.

Thus, the aim of the present paper is a comparative theoretical and experimental study of the influence of the two-dimensional PC waveguide and embedded into index- and gain-guided VCSEL cavities on transverse optical mode behavior.

In this paper, we analyze effective indices of optical modes in the PC defect waveguide with gain-guided or index-confined regions in order to investigate the modes and define single-mode conditions. This method makes no assumptions about the effective refractive index of the two-dimensional PC and the PC-waveguide core size, and, thus, it enables single-mode conditions to be defined more correctly than in [5,6].

2. THEORETICAL MODEL AND RESULTS

Recently, many VCSEL structures incorporating PCs have been proposed [4-7]. The structures with air-holes made through layers of top DBR can be easily fabricated using modern etching techniques and technology. But these structures have a modulation of refractive index in three dimensions which makes these structures difficult for theoretical consideration. It has been proposed [6] to use the etching dependence factor to describe the influence of the depth of the air holes on the cavity modes. They have shown that the influence of PC grows with increasing depth, which looks quite reasonable.

In this paper, we assume that the transverse PC waveguide embedded into VCSEL cavity has air-holes which go through the active region and both mirrors. We believe that the optical effects investigated here will have an influence on cavity modes as the depth of the etching is increased [6]. Such simplification allows us to consider the optical effects resulting from index or gain guidances taking place in practical VCSELs.

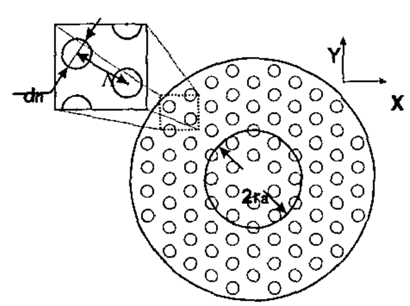

Figure 1. Theoretically investigated structure.

The investigated structure is shown in Fig. 1. It is a two-dimensional system taking into account effective refractive indices provided by gain-guided and index-guided regions with

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radius r_a. The photonic crystal is composed of hexagonally arranged air-holes with diameter d_h and center-to-center spacing Λ. The main material of the PC where holes are situated is GaAs with 3.53 refractive index, all results are obtained for 0.95 μm wavelength.

The transverse optical modes describe by scalar Helmholtz equation are solved numerically with absorbing boundary conditions accordingly to:

$$\nabla_T^2 \psi_j(x,y) + \left\{ \overline{n}^2(x,y) k_0^2 - \beta_j^2 \right\} \psi_j(x,y) = 0, \quad (1)$$

$$\left(\nabla_T - i\overline{n}\ (x,y) k_0 \right) \psi_j(x,y) = 0, \quad (2)$$

where ∇_T is the transverse Hamiltonian; $\psi_j(x,y)$ is the transverse electrical field pattern of j-th mode; $\overline{n}(x,y)$ is the refractive index pattern; $k_0 = 2\pi/\lambda$ is vacuum preparation constant; λ is the wavelength of optical wave; $\beta_j = n_j k_0$ is the j-th mode propagation constant and n_j is the mode effective index.

The transverse distribution of the refractive index according to Fig.1 can be defined in oxide-confined and proton-implanted VCSELs as follows (using [9,10]):

$$\overline{n}(x,y) = \begin{cases} n + i\dfrac{g\lambda}{4\pi}, & r \le r_a \\ n - \Delta n, & r > r_a \\ 1, & in\ \ holes \end{cases}, \quad (3)$$

where n is the refractive index of passive GaAs region; g is the gain; r_a is the oxide or proton confinement radius correspondingly in oxide-confined or proton-implanted VCSEL; Δn is the effective refractive index step between active and passive regions of a VCSEL in the transverse plane.

The effective refractive index step Δn taking into account influences of the oxide appertured, carrier and thermal induced change of refractive index can be defined using the equation [9]

$$\Delta n = \Delta n_{ox} + \Delta n_a, \quad (4)$$

where Δn_{ox} is the refractive index step provided by the oxide in oxide-confined VCSEL; $\Delta n_a = \Delta N\, \partial n/\partial N + \Delta T\, \partial n/\partial T$ is the refractive index step provided by effects of carrier injection and heating in active region; ΔN is the difference of carrier concentration between center of active region and edge of oxide aperture; and ΔT is the temperature difference between center of active region and edge of oxide aperture.

Effective mode indices computed for the described gain-guided structures as a function of d_h/Λ ratio are presented in Fig. 2. The fundamental space-filling (FSF) mode presented here is a PC cladding mode with a larger propagation constant in comparison with other cladding modes. Thus, the FSF mode characterizes a border between waveguiding and leaking modes of the waveguide. The single-mode in the waveguide lies up to $d_h/\Lambda < 0.47$ in comparison with passive, where it limited by $d_h/\Lambda < 0.4$ condition. The most important result we found from the figure is a that the mode in the waveguide is confined mainly by PC as opposite to gain guiding.

Fig. 3 shows the effective mode indices found for the described gain-guided and index-guided structures as a function of the confinement radius r_a. The gain-guided structure is still single-mode and effective mode indices are stable at all confinement radiuses r_a. It also means that the gain-guided structure can be single-mode at large confinement radiuses r_a in comparison with conventional gain-guided VCSELs. Using [10] we also can conclude, that the gain-guided waveguide structure consisting of a single-mode PC waveguide will have fixed effective mode indices and mode wavelengths in the laser spectra. The index-guided VCSEL structure demonstrates multimode properties, but we did not present all the modes of this structure in Fig. 4 due to their large number. Index guiding provided by the oxide dominates over index guidance provided by the PC and mode indices strongly depend on the confinement size r_a.

In practical VCSELs the carrier and temperature induced refractive index can play a significant role especially in small apertured devices. As we noted above, this index change is taken into account the second term in equation (4), defined as Δn_a. In this section we do not define this parameter but we use its value [9] in the theoretical model in order to prevent the influence of active conditions on modes in gain-guided VCSELs assuming $\Delta n_{ox} = 0$.

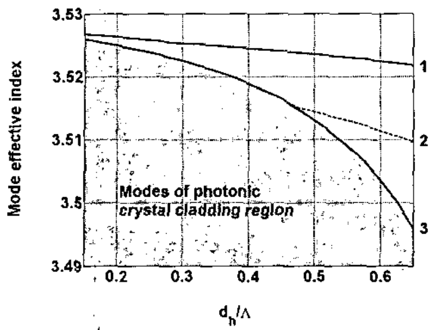

Figure 2. Effective mode index in gain-guided VCSELs as a function of d_h/Λ ratio for a structure with $\Lambda = 2$ microns and $r_a = 2$ microns. 1- LP_{01} - like mode, 2 - LP_{11} - like mode, and 3 – FSF mode.

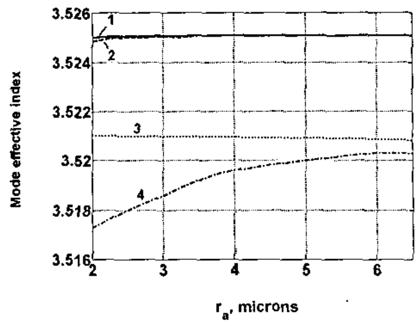

Figure 3. Effective mode index in gain-guided and index-guided VCSELs combined with single-mode PC waveguide at $d_h/\Lambda = 0.35$, $\Lambda = 2$ microns and $\Delta n_{ox} = 0.033$ as a function of optical confinement r_a. 1 - LP_{01} - like mode in gain-guided VCSEL, 2 - LP_{01} - like mode in index-guided VCSEL, 3 - FSF mode in gain-guided VCSEL, and 4 – LP_{11} - like mode in index-guided VCSEL.

Fig. 4 demonstrates effective mode indices computed as a function of Δn_a for a confinement radius of 2 microns. As we can see from this figure, the structure is single-mode in Δn_a range from 0 to 0.003. Thus, we can conclude, that the relatively large change of refractive index Δn_a provided mainly by heating of active layer by the injected current results in a switching of mode conditions. Thus, the current change can result in switching from single-mode to multi-mode operation. More detailed theoretical investigations shows that the optical spectrum of lasers even broadens additionally due to interaction of optical modes confined by both the PC defect and 'native" VCSEL cavities.

In order to investigate the thermal lensing effect experimentally, we have fabricated the single-mode PC waveguide channels in the top Bragg mirrors of the VCSELs using focused ion beam etching. Spectral characteristic of one of fabricated devices is presented in Fig. 5. It shows multimode operation due to the thermal lensing effect.

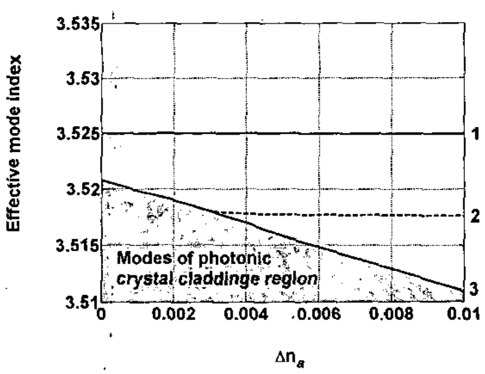

Figure 4. Effective mode indices as a function of the refractive index step Δn_a. $r_a = 2$ microns. 1- LP_{01} - like mode, 2 - LP_{11} - like mode, and 3 – FSF mode.

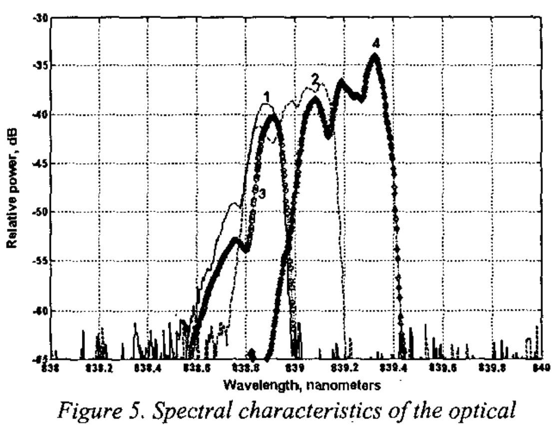

Figure 5. Spectral characteristics of the optical radiation of fabricated device with $r_a = 7\,\mu m$, $d_h = 120\,nm$, $\Lambda = 350\,nm$, $d_h/\Lambda = 0.34$. 1- Proton-implanted VCSEL at injected current $I=1.5\,I_{th}$ before etching; 2- same VCSEL at injected current $I=2.5\,I_{th}$ before etching; 3- same VCSEL at injected current $I=1.5\,I_{th}$ after etching at; 4- same VCSEL at injected current $I=2.5\,I_{th}$ after etching.

3. CONCLUSIONS

In the present paper we have investigated the transverse optical modes in waveguides created by a defect in a two-dimensional PC merged with active waveguides provided by gain-guided and index-guided mechanisms in VCSELs.

Assuming small influence of thermal lensing effect, it was shown that index-guiding provided by the oxide aperture dominates over guiding provided by the PC region in most cases when the oxide is not at a node position. The oxide at a node position has minimal influence on optical modes, and the VCSEL is completely gain-guided. In such cases, the oxide focuses only injected carriers, but mode control is provided completely by PC waveguide. Investigations of gain-guided structures show dominance of index guidance over gain-guidance. They can achieve a single-mode at $d_h/\Lambda < 0.47$, which covers larger region of d_h/Λ ratios in comparison with passive PC waveguides. The mode control is provided mainly by the PC in oxide-confined structures with the oxide at the node position.

The influence of the size of the gain or the index confinement with fixed size of single-mode PC defect waveguide on modes was investigated. Gain-guided structures demonstrated stable single-mode operation at all sizes of the gain confinement, but index-guided structures showed large dominance of index-guiding. In other words, the optical mode is limited by the index confinement effects, but not by the single-mode PC waveguide. The influence of thermal lensing effects was considered by introducing the index guidance effect into the theoretical model. It was shown that the increase of the refractive index in the core region formed by oxide or proton implant as a result of increased current injection leads to dominance of the index waveguiding in the confining region over the PC waveguiding.

Thus, the most promising approach for single-mode and stable VCSELs with incorporated two-dimensional PCs is to introduce the single-mode PC waveguide in the top DBR of the oxide confined VCSEL. The oxide has to be at a node position, where the mode control by the oxide is minimal. This produces a VCSEL structure where the oxide will focus carriers into the active region and the PC waveguide will control the optical modes. And the oxide confinement size has to be large in order to minimize the thermal lens effect. More concrete recommendations can be obtained in terms of a three-dimensional theoretical model of optical field in VCSEL cavity connected with drift-diffusion model of injected carriers.

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